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14. ABSTRACT Experiments were conducted on deformation and breakup properties of turbulent round liquid jets in uniform gaseous crossflows. Pulsed shadowgraph and holograph observations were obtained for turbulent round liquid jets injected normal to air crossflow in a shock tube. The onset of turbulent primary breakup approached the jet exit, approximating breakup conditions at large Weber numbers. Ligament diameters increased with increasing distance from the jet exit, becoming comparable to the radial integral scale of the liquid turbulence near the end of the liquid column. The correlation between drop Sauter mean diameters and streamwise distance along the liquid jet was not affected by the crossflow, suggesting that turbulent primary breakup dominated aerodynamic effects near the liquid surface. Drop velocities after turbulent primary breakup in crossflow were independent of drop size, with streamwise drop velocities comparable to mean streamwise liquid velocities and cross stream drop velocities somewhat larger than the characteristic velocity of the liquid jet in the cross stream direction. Breakup of the liquid column as a whole approximated the total times of breakup of drops subjected to shock wave disturbances in the shear breakup regime. The mean drop mass flux over the downstream projected area of the liquid column due to turbulent primary breakup at the liquid surface could be correlated by a surface efficiency factor that was small at the onset of breakup but increased to a value near unity as the end of the liquid column was approached.

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Liquid Breakup in Dense Sprays

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Liquid Breakup in Dense Sprays

Abstract

Liquid breakup and turbulence generation were studied due to their relevance to the dense combusting sprays found near the fuel injectors of propulsion systems; in particular, secondary and primary liquid breakup are important because they are rate-controlling processes of dense sprays and fix initial conditions of dilute sprays. Past work has shown that secondary drop breakup should be treated as a rate process and have provided the temporal properties of secondary drop breakup needed for this purpose. Current work addressed three aspects of primary liquid jet breakup, as follows: (1) breakup of round nonturbulent liquid jets in gaseous crossflows because this is a classical spray atomization configuration of particular interest for afterburners and missile propulsion systems, (2) breakup of round turbulent liquid jets in gaseous crossflows because most practical injectors introduce some degree of turbulence to liquid flows in injector passages, and (3) breakup of aerated-liquid jets in gaseous crossflows because this configuration has attractive atomization and penetration properties for missile propulsion systems. Measurements were made using pulsed holography and shadowgraphy whereas phenomenological analysis was used to help interpret and correlate the measurements. The following information was sought for the three spray configurations that were considered: definition of spray breakup regimes, liquid jet trajectories, conditions for the onset of breakup, conditions for jet breakup as a whole, drop size and velocity distributions after breakup as a function of distance along the jet and rates of breakup as a function of distance along the jet. These results have been obtained for the first flow with current work in progress for the other two flows.

Turbulence generation is the main source of turbulence in dense sprays; it consists of drop (particle) wake disturbances embedded in a continuous turbulent interwake region. Both regions involve unusual flows that have received little attention in the past: the particle (drop) wakes are laminar-like turbulent wakes that are observed for intermediate Reynolds number spheres in turbulent environments whereas the turbulent interwake region consists of isotropic turbulence in the little-studied final decay period. Past work found the properties of these flows for monodisperse particle (drop) flows; current work has considered these properties for more practical polydisperse particle (drop) flows.

Liquid Breakup in Dense Sprays

Objectives:

Primary liquid breakup and turbulence generation by dispersed phases (particles or drops) are being studied due to their relevance to spray combustion processes of air breathing propulsion systems and liquid rocket engines of interest to the Air Force. The specific objectives of the two phases of the study are as follows:

(i) **Liquid Breakup**. Complete measurements of primary breakup properties for the following conditions: (1) round nonturbulent liquid jets in gaseous crossflows because this is a classical spray atomization configuration of interest for afterburners and missile propulsion systems, (2) round turbulent liquid jets in gaseous crossflows because most practical injectors introduce some degree of turbulent disturbance to liquid flows in injector passages, and (3) aerated-liquid jets in gaseous crossflows because this configuration has attractive atomization and penetration properties for missile propulsion systems. In all cases, the following information is sought: definition of breakup regimes, liquid jet trajectories, conditions for the onset of breakup, conditions for jet breakup as a whole, drop size and velocity distributions after breakup as a function of distance along the jet and rates of liquid breakup as a function of distance along the jet.

(ii) **Turbulence Generation**. Complete conditional measurements of interwake turbulence properties needed for a rational description of turbulence generation properties, and complete conditional measurements of the mean and fluctuating properties of particle wakes in turbulent environments representative of turbulence generation processes, considering polydisperse particle flows as dispersed phases. Complete theoretical interpretation of the measurements using classical methods of describing isotropic turbulence for the properties of interwake turbulence fields and similarity theory for the properties of particle wakes.

Status of Effort:

Progress toward achieving the research objectives of the liquid breakup and turbulence generation phases of the investigation is discussed, in turn, in the following:

Liquid Breakup. There were three main contributions to improved understanding of liquid breakup processes in dense sprays during the report period, as follows: (1) measurements, numerical computations and phenomenological analysis of the primary breakup properties of round nonturbulent liquid jets in gaseous crossflows were completed. (2) Measurements and phenomenological analysis of the primary breakup properties of round turbulent liquid jets in gaseous crossflows were initiated. (3) Finally, measurements and phenomenological analysis of the primary breakup properties of round aerated-liquid jets in gaseous crossflows were initiated. In all three cases measurements of drop size and velocity distributions after breakup and rates of liquid breakup are sought with the results interpreted and correlated using phenomenological analysis.

Turbulence Generation. There were two main contributions to improved understanding of turbulence generation during this report period, as follows: (1) new measurements allowed the properties of the interwake region of turbulence generation processes to be extended from earlier findings for monodisperse particle flows to more practical polydisperse particle flows, and (2) new measurements allowed the properties of the particle wake region of turbulence generation processes to be extended from earlier findings for monodisperse particle flows to more practical polydisperse particle flows.

Accomplishments/New Findings:

Research highlights for the liquid breakup and turbulence generation phases of the present investigation are discussed, in turn, in the following:

Liquid Breakup. Past experimental studies have established the temporal properties of secondary drop breakup for drops exposed to shock-wave disturbances (a step change in the ambient gas velocity around a drop to simulate breakup processes after drops appear in a continuous gas flow as a result of primary breakup), see Aalburg et al. (2003), Chou and Faeth (1998), Chou et al. (1997), Dai and Faeth (2001), Faeth (1996), and Hsiang and Faeth (1992,1993,1995), and have initiated studies of the breakup of round nonturbulent liquid jets in crossflow, see Mazallon et al. (1999). All of these studies were limited to large liquid/gas density ratios. Current work has considered three primary liquid breakup processes, as follows: (1) primary breakup of round nonturbulent liquid jets in uniform gaseous crossflows, (2) primary breakup of round turbulent liquid jets in uniform gaseous crossflows, and (3) primary breakup of aerated-liquid jets in uniform gaseous supersonic crossflows. The latter two of these flows were also limited to large liquid/gas density ratios.

Large Density-Ratio Experiments Using SF6. An experimental investigation of the deformation and breakup properties of turbulent round liquid jets in uniform gaseous crossflows was undertaken. Pulsed shadowgraph and holograph observations were obtained for turbulent round liquid jets injected normal to air crossflow in a shock tube. Crossflow velocities of the air behind the shock wave relative to the liquid jet were subsonic (36-90 m/s) and the air in this region was at normal temperature and pressure. Liquid injection was done by a pressure feed system through round tubes having inside diameters of 1 and 2 mm and length-to-diameter ratios greater than 100 to provide fully-developed turbulent pipe flow at the jet exit. Test conditions were as follows: water and ethyl alcohol as test liquids, crossflow Weber numbers based on gas properties of 0-282, streamwise Weber numbers based on liquid properties of 1,400-32,200, liquid/gas density ratios of 683 and 845, and jet exit Reynolds numbers based on liquid properties of 7,100-48,200, all at conditions where direct effects of liquid viscosity were small (Ohnesorge numbers were less than 0.12). The major conclusions of the study are as follows:

(1) Streamwise mean liquid jet surface velocities varied to a negligible degree in the streamwise direction and approximated mean liquid velocities at the injector exit, suggesting that effects of streamwise gas drag on the liquid jet were small.

(2) The onset of turbulent primary breakup always occurred at some distance from the jet exit but approached the exit, approximating atomization breakup conditions, at large $We_{L\Lambda}$.

(3) Ligament diameters due to turbulent primary breakup increased with increasing distance from the jet exit, with these diameters becoming comparable to the radial integral scale of the liquid turbulence as the end of the liquid column is approached.

(4) The correlation between drop SMD and streamwise distance along the liquid jet was not affected by the crossflow, suggesting that turbulent primary breakup dominates aerodynamic effects for present test conditions near the liquid surface. Similar to ligament diameters, the SMD was comparable to the radial integral scale of the liquid turbulence as the end of the liquid column was approached.

(5) Drop velocities after turbulent primary breakup in crossflow were independent of drop size with streamwise drop velocities comparable to mean streamwise liquid velocities and cross stream drop velocities somewhat larger than the characteristic velocity of the liquid jet in the cross stream direction, similar to drop velocities after primary breakup of nonturbulent round liquid jets in crossflow.

(6) Breakup of the liquid column as a whole approximated the total times of breakup of drops subjected to shock wave disturbances in the shear breakup regime, yielding $t_b/t^* = 1.61$ and $x_b/d_j = 5.20$ which are smaller than the results for nonturbulent round liquid jets indicating enhancing effects of liquid turbulence on liquid column breakup.

(7) The mean drop mass flux over the downstream projected area of the liquid column due to turbulent primary breakup at the liquid surface could be correlated by a surface efficiency factor that was small at the onset of breakup but increased to a value near unity as the end of the liquid column was approached. The results were in good agreement with earlier measurements for nonturbulent round liquid jets.

Primary Breakup of Round Nonturbulent Liquid Jets in Gaseous Crossflows. A computational and experimental study of the deformation and breakup properties of nonturbulent round liquid jets in uniform gaseous crossflows was undertaken seeking to develop numerical predictions of these properties at conditions that are difficult to address using experiments. The time-dependent incompressible two-dimensional Navier-Stokes equations were solved in the gas and liquid phases in conjunction with the level-set method to determine the position of the liquid/gas interface of the deforming liquid jets. The computations were evaluated satisfactorily based on earlier measurements of flows over solid circular cylinders as well as present measurements of the properties of nonturbulent round liquid jets in crossflow (liquid jet cross stream deformation, liquid jet streamwise deformation and deflection, and breakup regime transitions). The main findings of the study were as follows: (1) remarkable similarities were observed between the deformation and breakup properties of nonturbulent round liquid jets in uniform crossflows and the secondary breakup properties of round liquid drops subjected to shock wave disturbances, (2) liquid/gas density ratio had a surprisingly small effect on the deformation and breakup of nonturbulent liquid jets subjected to uniform crossflows for liquid/gas density ratios greater than thirty (30) and when effects of liquid viscosity are small

(Ohnesorge numbers less than 0.1), (3) the crossflow Reynolds number had little effect on liquid breakup properties for values larger than 50, however, as the small Reynolds number, Stokes flow regime is approached, liquid jet resistance to deformation and breakup increases significantly due to increased liquid column drag coefficients, and (4) a liquid column deformation and breakup regime map, plotted as a function of the ratio of column-drag-force/column-viscous force ratio ($We^{1/2}/Oh$ where We is the crossflow Weber number and Oh is the crossflow Ohnesorge number) and the surface-tension-force/liquid-viscous-force ratio (1/Oh) yielded deformation and breakup regime boundaries at large Oh that were relatively independent of the other parameters of the flow and also quantified the relatively small effect of liquid/gas density ratio on flow regime transitions at these conditions. See Aalburg et al. (2003,2004) for a complete discussion of these results.

Primary Breakup of Turbulent Liquid Jets in Uniform Crossflow. An experimental study of the deformation and breakup properties of round turbulent liquid jets in uniform gaseous crossflows was undertaken seeking to develop information about this process in order to evaluate effects of turbulent disturbances within the liquid jet, frequently introduced by practical liquid injector passages, on jet breakup properties. Extensive work on this primary breakup process has been carried out earlier in this laboratory. This work was limited, however, to the primary breakup of round turbulent liquid jets in still gases with fully-developed turbulent pipe flow at the injector exit, see Sallam and Faeth (2003), Sallam et al. (2002), Wu and Faeth (1993,1995) and Wu et al. (1992,1995). Present measurements were carried out considering round liquid jets for various liquids produced using long injector passage lengths (greater than 50 injector diameters) with sufficiently-large injector Reynolds numbers to ensure fully-developed turbulent pipe flow at the injector exit, based on criteria developed by Wu et al. (1995). Crossflows were developed using the subsonic flow (relative to the jet) behind propagating shock waves in a shock tube and subsonic flows in a subsonic wind tunnel (the former to observe breakup properties along the liquid surface and the latter to observe breakup of the liquid jet as a whole). Observations of the primary breakup process were made using pulsed shadowgraphy and holography. Measurements planned for this study include: liquid jet cross stream deformation, liquid jet streamwise deformation and deflection, breakup regime transitions, onset of shear breakup along the liquid surface, the variation of ligament sizes, drop sizes and velocities after breakup as a function of distance along the liquid surface, and rates of liquid breakup as a function of distance along the liquid surface.

This work is still in progress but results thus far point to the importance of liquid turbulence properties on liquid breakup processes. In particular, light gases are far less effective for creating vorticity in the liquid than injector passage walls and liquid breakup simply cannot occur in the absence of liquid phase vorticity. Thus, many of the results in this case involve properties similar to those observed for primary round turbulent liquid jets in still gases, and are only mildly perturbed by effects of the crossflow.

Primary Breakup of Round Aerated-Liquid Jets in Supersonic Gaseous Crossflow. An experimental investigation of the primary breakup properties of round aerated-liquid jets in the annular flow regime exposed to a supersonic crossflow was undertaken. Single- and double-pulse shadowgraphy and holography were used to study the properties of the conical liquid sheet that extends from the jet exit for finite degrees of aeration (gas/liquid mass flow rate ratios

greater than 2%) as well as the outcomes of primary breakup in the dense-spray region near the liquid jet itself. The results showed that the gas jet along the axis of the annular flow leaving the injector passage is underexpanded so that the excess pressure of the flow in this region forces the annular liquid sheet into a conical shape that extends from the injector exit. Primary breakup occurred in a similar manner along both the upstream and downstream sides of the liquid jet (relative to the crossflow) which suggests that aerodynamic effects due to the crossflow are relatively weak near the jet exit. Surface velocities of the liquid sheet were measured and were used to develop correlations for the liquid sheet thickness and for the penetration of the sheet prior to its breakup as a whole. Sizes of ligaments and drops were measured along the liquid surface and were found to have constant diameters of 0.029 and 0.043 mm, respectively, independent of position along the liquid sheet and wide ranges of aeration levels, liquid/gas momentum flux ratios, injector exit passage diameters, liquid/gas momentum flux ratios, injector exit passage diameters and liquid properties for the ranges of these variables considered during the present investigation. Finally, drop size distributions satisfied Simmons' universal root-normal drop size distribution function with the ratio of the mass median drop size, MMD, to the Sauter mean drop size, SMD, or MMD/SMD = 1.07, which implies more nearly monodisperse drop size properties after aerated-liquid breakup than is encountered for other primary and secondary breakup properties.

Findings thus far have made significant progress toward understanding the breakup properties of aerated-liquid jets. An important finding is that crossflows, even supersonic crossflows, appear to have little effect on breakup because the process is dominated by the external expansion process of the gas flow at the axis of the annular flow near the injector exit. Given this finding, subsequent study of this flow can be carried out without needing time in a supersonic or subsonic wind tunnel, which is invariably limited. This study needs to complete measurements similar to those available for primary round nonturbulent liquid jets in uniform crossflows, e.g., ligament and drop sizes (after breakup) as a function of distance along the liquid surface, drop velocities after breakup as a function of distance along the liquid surface, rates of liquid breakup as a function of distance along the liquid surface, and conditions for breakup of the liquid sheet as a whole.

Turbulence Generation. Experimental and mathematical investigation of the properties of the laminar-like turbulent wake region behind particle in homogeneous turbulent dispersed flows, and the properties of the turbulent inter-wake region generated by uniform fluxes of polydisperse particle phases moving through air at standard temperature and pressure was undertaken. Combined with the earlier study of Chen and Faeth (2001) involving monodisperse particle phases, test conditions were as follows: particle phases consisting of monodisperse and binary mixtures of nearly monodisperse glass beads having diameters of 0.5, 1.1 and 2.2 mm, with corresponding particle Reynolds numbers of 106, 373 and 990; particle volume fractions less than 0.003%; direct rates of dissipation of turbulence by particles less than 4%; and turbulence generation rates sufficient to yield streamwise relative turbulence intensities of 0.2-1.5%. The major conclusions of the study are as follows:

(1) The measurements of the mean velocities within the wake disturbances observed during the present turbulence generation processes were in good agreement with the theoretical predictions for laminar-like turbulent wakes based on studies of Wu and Faeth (1994,1995),

for spherical particles at intermediate Reynolds numbers in turbulent environments. The properties of velocity fluctuations within the wake disturbances observed during the present turbulence generation processes were also in qualitative agreement with the properties of the laminar-like turbulent wakes observed in Wu and Faeth (1994,1995).

(2) Within the final decay period, rates of dissipation are substantially enhanced compared to conventional isotropic turbulence at large turbulence Reynolds numbers having similar values of L_u and $\bar{u}'$. In addition, macro/micro length scale ratios (e.g., L_u / λ) decrease with increasing turbulence Reynolds numbers in the final decay period as opposed to behavior typical of conventional isotropic turbulence at large turbulence Reynolds numbers where these ratios increase with increasing turbulence Reynolds numbers. Thus, flows in the final decay period can exhibit a large range of scales even though their turbulence Reynolds numbers are small.

(3) Dimensional analysis based on the assumption that turbulence decay in the transition region is dominated only by dissipation yielded the result that dimensionless integral scale, A, is proportional to the -1 power of Re_λ and that the ratio of length scales, L_u / λ, has a constant value on the order of unity in this region. Finally, the appearance of a transition region with a narrow range of scale was shown to be a natural outcome of the variation of macro scales (integral scales) and micro scales (Taylor and Kolmogorov scales) in the initial and final decay regions of turbulence that bound in the transition region.

(4) A large range of scales where effects of viscosity are small, yielded a –5/3 Kolmogorov inertial-decay region of the energy spectra, for the same reasons that inertial-decay regions are observed in conventional turbulence at large turbulence Reynolds numbers. The wave number range of the inertial decay region of inter-wake turbulence in the final decay period, taken largely as the wave number range between kL_u = 1 and $k\ _K$ = 1, decreases with increasing turbulence Reynolds number, consistent with the length scale ratios.

(5) From analysis of energy spectra, a relationship between velocity fluctuations and the rates of dissipation could be derived and showed that rms velocity fluctuations are proportional to the 10/17 power of the rate of dissipation. The results of this derivation are consistent with the empirical finding developed by analogy with the approach used by Batchelor and Townsend (1948a,1948b) which indicated that relative turbulence intensities were proportional to the 1/2 power of the dissipation factor. The new derivation yielded a better correlation of relative turbulence intensities as a function of dissipation factor but more importantly is based on the fundamental properties of turbulence in the turbulent inter-wake region as opposed to add assumptions to extend earlier findings of isotropic grid-generated turbulences.

Early studies showed that turbulence generation by particles (drops) involved particle wakes embedded in a turbulent interwake region (Parthesarathy and Faeth 1990a,b; Mizukami et al. 1992). Wu and Faeth (1993,1994,1995) subsequently showed that the wakes behaved like laminar wakes but with fast mixing due to the presence of turbulence (commonly referred to as "laminar-like turbulent wakes"). Subsequently, Chen et al. (2000) and Chen and Faeth (2000,2001), considering turbulence generation for monodisperse particle flows, showed that the turbulent interwake region consisted of isotropic turbulence in the rarely observed final-decay

period defined by Batchelor and Townsend (1948). The current work of Lee et al. (2003) extends these observations to the turbulent interwake region of more practical polydisperse particle flows, using wake-discriminating laser velocimetry.

Chen and Faeth (2001) developed an analogy between grid-generated isotropic turbulence and particle-generated isotropic turbulence, when both were in the final-decay period. This yielded a very useful correlation between relative turbulence intensities in the streamwise and cross-stream directions, ($\overline{u}'$ and $\overline{v}'$)/U_p, where U_p is the mean streamwise velocity of the particles relative to the gas, and the dimensionless rate of dissipation of mechanical energy of the particles, D. During the present investigation, mixing rules were developed to extend these ideas to polydisperse particle flows based on dissipation weighting of the effect of each particle size group. The resulting correlation of the measurements exhibits a universal correlation for both monodisperse and polydisperse sized particles according to the square root of D, as suggested by the theory.

Other experiments completed during this report period involved wake-discriminating measurements of energy spectra and characteristic length scales for the turbulent interwake region of polydisperse particle flows. A remarkable feature of these results was the large range of length scales observed (up to 1000:1) even though turbulence Reynolds numbers were small (less than 4). Present results yielded the ratios of the streamwise integral length scale, L_u, to the Taylor dissipation scale, λ, as a function of the turbulence Reynolds number, Re_λ. Surprisingly, L_u/λ decreases with increasing Re_λ, for interwake turbulence in the final-decay period, which is just opposite to the behavior of conventional turbulence. The interwake region also involves rates of turbulence dissipation up to 1000 times larger than conventional turbulence at comparable outer scales, accounting for past problems of turbulence models to predict the properties of this flow (Lee et al. 2003).

The final phases of this study further considered the properties of laminar-like turbulent wakes and the turbulent interwake region for polydisperse (actually binary) particle phases (note that based on current understanding of effects of polydisperse particle phases, the extension of current findings for binary particle phases to polydisperse particle phases is trivial). These results indicated that the ambient turbulence level created by turbulence generation critically affected the properties of laminar-like turbulent wakes. This turbulence is in the final decay period, however, so that the nature of the particles used to create this turbulence is not critical, i.e., such flows do not have significant memories of the processes that formed them.

The other phase of this work considered the nature of length scales for turbulence generation properties in the final decay period. The first part of this work, however, actually considered grid-generated isotropic turbulence in the initial-decay period as a baseline. Present measurements of L_u/λ for these flows yielded values typical of earlier measurements of this ratio for grid-generated isotropic turbulence in the initial-decay period. These results also yielded the typical behavior of isotropic turbulence in the initial-decay period where L_u/λ increases with increasing values of Re_λ, i.e., the range of length scales in this flow increases with increasing Re_λ because the large scales are little affected by fluid viscosity (measured by Re_λ) whereas, the smaller scales become smaller with increasing Re_λ as a direct result of the scaling properties of the Kolmogorov microscale which is a measure of the smallest scales of turbulence.

Finally, an interesting trend of the final-decay period of isotropic turbulence found in the interwake region of turbulence generation processes is that the range of L_u/λ decreases with increasing Re_λ, which is exactly opposite to the behavior of conventional isotropic turbulence in the initial-decay period. This implies progressive reduction of L_u/λ with increasing Re_λ until this ratio approaches unity near $Re_\lambda \approx 20$, after which this ratio increases with increasing Re_λ typical of conventional isotropic turbulence. Work during the present report involved direct measurements of the energy spectra of isotropic turbulence in the final-decay period so that the range of the spectra could be observed directly. These results showed two things: (1) the range of the spectra became progressively smaller as L_u/λ approached unity, and (2) these spectra decay with increasing wave number according to the –5/3 power of the wave number as predicted by Kolmogorov for conventional isotropic turbulence more than fifty years ago. Reexamination of the Kolmogorov derivation, however, revealed that properties of the final-decay period satisfied the assumptions of the initial-decay period equally well (the main requirement being the presence of a large range of length scales between the macro- and micro-scales of the turbulence). In this case, the ratio, L_u/λ, grows with decreasing Re_λ because the flow is dominated by sparse helical vortices whose axes are aligned in the streamwise direction. Then, the diameter of helix grows by the inviscid effect of induced vorticity whereas the scale of the microscales grows very slowly by viscous encroachments at small scales: the net effect is that the ratio L_u/λ increases with decreasing Re_λ, or what is the same with increasing distance from the particle source of the turbulence.

This behavior implies that turbulence essentially disappears at the transition condition at $Re_\lambda \approx 20$ where $L_u/\lambda \approx 1$. This region would be very interesting to observe but it is difficult to reach without providing ultra-low turbulent disturbances of the wind tunnel in the absence of particle flows. Naturally, at the start of the study we did not know enough about the flow to recognize this unusually stringent requirement; therefore, transition conditions were not achievable during the present study.

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Refereed Publications:

Aalburg, C., van Leer, B., Faeth, G. M., and Sallam, K. A., "Properties of Nonturbulent Round Liquid Jets in Uniform Gaseous Crossflows," *Atom. Sprays,* Vol.15, No. 3, 2005, pp. 249-270.

Sallam, K.A., Aalburg, C., and Faeth, G.M., "Breakup of Round Nonturbulent Liquid Jets in Gaseous Crossflow," *AIAA J,* Vol. 42, No. 12, 2004, pp. 2529-2540.

Lee, K., "Experimental Study of Particle-Generated Turbulence in the Final Decay Period", Ph.D Dissertation, University of Michigan, Ann Arbor, MI, 2004.

Lee, K., Aalburg, C., Diez, F. J., Faeth, G. M. and Sallam, K. A., "Breakup of Round Turbulent Liquid Jets in Gaseous Crossflows," AIAA J., submitted.

Lee, K. and Faeth, G. M., "Particle-Generated Isotropic Turbulence in the Final-Decay Period," AIAA J., submitted.

Sallam, K.A. and Faeth, G.M., "Surface Properties During Primary Breakup of Turbulent Liquid Jets in Still Air," *AIAA J.*, Vol. 41, No. 8, pp. 1514-1524, 2003.

Aalburg, C., van Leer, B. and Faeth, G.M., "Deformation and Drag Properties of Round Drops Subjected to Shock Wave Disturbances," *AIAA J.*, Vol. 41, No. 12, pp. 2371-2378, 2003.

Lee, K., Chen, J.-H. and Faeth, G.M., "Properties of Particle-Generated Turbulence in the Final-Decay Period," *AIAA J.*, Vol. 41, No. 7, pp. 1332-1340, 2003.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Primary Breakup of Aerated-Liquid Jets in Uniform Gaseous Crossflow," *Atom. Sprays,* submitted.

Interactions/Transitions:

a. Participation/presentation at meetings, conferences, seminars, etc.:

Lee, K., Diez, F. J. and Aalburg, C., "Breakup Properties and Trajectories of Turbulent Round Liquid Jets in Gaseous Crossflows," APS Division of Fluid Dynamics 58th Annual Meeting, Chicago, IL, November, 2005, in preparation.

Lee, K., Diez, F. J., Faeth, G. M., Aalburg, C. and Sallam, K. A., "Breakup of Round Turbulent Liquid Jets in Air Crossflows," ILASS-America 2005, Irvine, CA, May, 2005.

Lee, K., Faeth, G. M. and Chen, J.-H., "Particle-Generated Isotropic Turbulence in the Final-Decay Period," 2005 APS March Meeting, Los Angeles, CA, March, 2005.

Aalburg, C., Faeth, G.M. and Sallam, K.A., "Primary Breakup of Round Turbulent Liquid Jets in Uniform Gaseous Crossflows," 43rd AIAA Aerospace Sciences Meeting, Reno, NV, No. 2005-0734, 2005.

Faeth, G.M., "Primary Breakup of Nonturbulent Round Liquid Jets in Gaseous Crossflows," Engineering Science and Mechanics Seminar, Virginia Tech, Blacksburg, Va, October, 2004.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Breakup of Aerated-Liquid Jets in Supersonic Crossflows," 42nd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2004-0970, 2004.

Aalburg, C., Sallam, K.A. and Faeth, G.M., "Properties of Nonturbulent Round Liquid Jets in Uniform Crossflows," 42nd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2004-0969, 2004.

Aalburg, C., Sallam, K.A., van Leer, B. and Faeth, G.M., "Properties of Nonturbulent Round Liquid Jets in Uniform Gaseous Crossflow," 56th Annual Meeting, American Physical Society, Division of Fluid Dynamics, Newark, NJ, 2003.

Sallam, K.A., Aalburg, C. and Faeth, G.M., ""Experimental Study of the Breakup of Nonturbulent Round Liquid Jets in Gaseous Crossflow," 56th Annual Meeting, American Physical Society, Division of Fluid Dynamics, Newark, NJ, 2003.

Sallam, K.A., Aalburg, C., and Faeth, G.M., "Primary Breakup of Round Nonturbulent Liquid Jets in Uniform Gaseous Crossflows," *Proceedings of the 19th Annual Conference of ILASS Europe*, Nottingham, UK, 2004.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Primary Breakup of Aerated-Liquid Jets in Uniform Gaseous Crossflows," *Proceedings of the 19th Annual Conference of ILASS Europe*, Nottingham, UK, 2004.

Sallam, K.A., Aalburg, C., Faeth, G.M., Lin, K.-C., Carter, C.D. and Jackson, T.A., "Primary Breakup of Aerated-Liquid Jets in Uniform Gaseous Crossflows," *Proceedings of the 17th Annual Conference of ILASS Americas,* Washington, DC, 2004.

Aalburg, C., Faeth, G.M. and Sallam, K.A., "Primary Breakup of Round Turbulent Liquid Jets in Uniform Gaseous Crossflows," 43rd AIAA Aerospace Sciences Meeting, Reno, NV, submitted.

Aalburg, C., Lee, K., Faeth, G.M. and Sallam, K.A., "Experimental Study of the Breakup of Turbulent Round Liquid Jets in Gaseous Crossflows," 57th Annual Meeting, American Physical Society, Division of Fluid Dynamics, Seattle, WA, 2004.

Faeth, G.M., "Measurements of Primary Breakup Properties in Dense Sprays, 17th Annual Conference of ILASS-Americas, Washington, DC, 2004.

Faeth, G.M., "Primary Breakup Properties of Round Pure-Liquid and Aerated-Liquid Jets in Gaseous Crossflows," AFOSR/ARO Contractors' Meeting in Chemical Propulsion, Tucson, AZ, 2004.

b. Consultation and Advisory Functions.

A paragraph describing interactions with AFRL Researchers during the past year is as follows:

Meetings at the start of the present investigation between C. Carter and T.A. Jackson of the Propulsion Directorate of AFRL at Wright-Patterson Air Force Base, OH, Steven Lin of Taitec, Inc., Beavercreek, OH and individuals at the University of Michigan, Ann Arbor, MI, developed a collaboration to study the primary breakup properties of aerated-liquid injectors in supersonic crossflow. There were two main objectives of the planned research, as follows: (1) to develop an improved pulsed holocamera that would have the capability to penetrate the dense spray region right up to the liquid surface and allow observations of the mechanisms and outcomes of primary breakup, and (2) to apply this technology to gain a better understanding of the primary breakup properties of aerated-liquid jets in supersonic crossflows. Given the experience of the AFRL personnel with laser-based optical diagnostics, pulsed holography techniques developed at the University of Michigan were substantially modified to obtain an improved holocamera system. The new holocamera was then used to observe the primary breakup properties of aerated-liquid jets for the large liquid/gas-density ratio and supersonic crossflow conditions of interest for missile propulsion system applications. Phenomenological analyses were used to help interpret and correlate the measurements for use by others. These observations have defined the topography of the flow, have provided some of the primary breakup properties of the flow, and have shown that the effect of even a supersonic crossflow on aerated-liquid breakup is relatively weak. These results have been summarized in a paper that has been submitted for publication (K.A. Sallam et al., "Primary Breakup of 'Aerated-Liquid Jets in Supersonic Crossflow," *Atomization and Sprays*, submitted). This collaboration involved several meetings per month at either AFRL, Wright-Patterson AFB, OH or the Department of Aerospace Engineering at the University of Michigan, Ann Arbor, MI.

c. Transitions

There were two activities of this nature during the report period, as follows:

Customer:

Dr. Hakam Mongia
Manager, Advanced Combustors Engineering
GE Aircraft Engines (GEAE)
One Neuman Way, MDE404
Cincinnati, OH 45215-1988

Subject Matter:

This involved transferring recent information developed during the currently-active grant concerning the breakup of round nonturbulent liquid jets in gas crossflows to GEAE. This information is being used to develop numerical simulations of the combustion systems of propulsion devices.

Customer:

Dr. David Hagen
VAST Power Systems, Inc.
Value-Added Steam Technologies
2824 South 17th Street
Elkhart, IN 46526-8713

Subject Matter:

This involved transferring recent information developed during the currently-active grant concerning the breakup of round aerated-liquid jets in supersonic air crossflow and also the breakup of round nonturbulent and turbulent liquid jets in gaseous crossflows to VAST Power Systems, Inc. This information is being used during the development of novel liquid-fueled combustion systems for power generation.

New Discoveries, Inventions or Patent Disclosures:

None

Honors/Awards:

a. During Grant/Contract Period (for G. M. Faeth):

Invited Plenary Lecture, "Mechanics of Fire Suppression by Halons and Halon Replacements," 6th International Conference on Technologies and Combustion for a Clean Environment," Porto, Portugal, 2001

Medal of Appreciation, Helwan University, El Mattaria, Cairo, Egypt, 2002

Invited James E. Peters Plenary Lecture, "Optical and Radiative Properties of Soot in Flame Environments," Spring Technical Meeting, Central States Section, The Combustion Institute, Pittsburgh, 2002

Invited Distinguished Lecture, "Soot Growth and Oxidation Properties of Premixed and Nonpremixed Flames," Dept. Chem. and Fuels Engr., University of Utah, 2002

Invited Plenary Lecture, "Soot Formation and Oxidation in Premixed and Nonpremixed Flame Environments," Spring Technical Meeting, Canadian Section, The Combustion Institute, Pittsburgh, 2002

Invited 2002 Distinguished Lecture, "Mechanisms of Fire Suppression by Halons and Halon Replacements," Mechanical Engineering and Mechanics Dept., Drexel University, Philadelphia, PA, 2002

Invited Plenary Lecture, "Properties of Postflame (Overfire) Turbulent Plumes in Still and Crossflowing Environments," 8th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, St. Louis, MO, 2002

Invited Plenary Lecture, "Dynamics of Secondary Drop Breakup — A Rate Controlling Process in Dense Sprays," ILASS-Europe 2002, Zaragoza, Spain, 2002

Invited Andrew H. Hines, Jr. Lecture, "Turbulence Generation by Drops in Sprays," Dept. Mech. Aero. Engr., University of Florida, Gainesville, FL, 2002

Fellow, American Physical Society (APS), 2003

National Associate (National Academy of Sciences, National Academy of Engineering, Institute of Medicine, National Research Council), 2003

Space Processing Award, American Institute of Aeronautics and Astronautics (AIAA), 2004

Alfred C. Egerton Gold Medal, The International Combustion Institute, 2004

Arthur B. Modine Distinguished University Professor of Aerospace Engineering, The University of Michigan, 2004

b. Lifetime Achievement Awards (all for G.M. Faeth):

Outstanding Achievement in Research Award, College of Engineering, The Pennsylvania State University (1979)

Fellow, ASME (1983)

Heat Transfer Memorial Award, ASME (1988)

Excellence in Research Award, College of Engineering, University of Michigan (1988)

Fellow, AIAA (1988)

Outstanding Engineering Alumnus, The Pennsylvania State University (1990)

Fellow, AAAS (1990)

Member, National Academy of Engineering (1991)

Distinguished Engineering Faculty Research Award, University of Michigan (1992)

Propellants and Combustion Award, AIAA (1993)

Stephen S. Attwood Award, University of Michigan (1993)

NASA Public Service Medal (1999)

Silver Shaft Award, Sigma Gamma Tau, The University of Michigan (2000)

Highly-Cited Researcher Certificate (for being among the 99 most-cited engineers in the world), Institute for Scientific Information (2000)

Medal of Appreciation, Helwan University, Cairo, Egypt (2002)

Fellow, APS (2003)

National Associate, National Academy of Engineering (2003)

Space Processing Award, AIAA (2004)

Alfred C. Egerton Gold Medal, The International Combustion Institute (2004)